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Modification of Optical Instruments for In-Stack Monitoring of Particle Size

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North Wales, PA

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MODIFICATION OF OPTICAL INSTRUMENT FOR IN-STACK MONITORING OF PARTICLE SIZE

by

A. L. Wertheimer
Leeds & Northrup Company
North Wales, Pa. 19454

Contract No. 68-02-3253

Project Officer

William D. Conner
Emission Measurement and Characterization Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
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16. ABSTRACT

A light scattering instrument for in-situ measurements of particles in the 0.2 to 20 micrometer diameter size range is described, and field test results are presented. The instrument is a modified version of an earlier prototype. The upper limit of the size response has been extended from 10 to 20 micrometers, and several component and packaging changes have been incorporated to make the unit more suited to stack particulate emission survey applications.

The completed instrument was tested at a coal-fired electric power generating facility. During the test a cascade impactor was used as a referee device and both instruments were run side by side in the outlet duct of the electrostatic precipitator. Results show an excellent correlation between the two instruments with regard to the identification of a 1 μm diameter peak in the particle size distribution. A second peak around 20 μm was defined by the optical instrument, but could not conclusively be confirmed through the impactor data. The optical instrument handled well during the field test.

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ABSTRACT

A light scattering instrument for in-situ measurements of particulates in the 0.2 to 20 micrometer diameter size range is described, and field test results are presented. The instrument is a modified version of a prototype built during a prior EPA contract, Number 68-02-2447. The upper limit of the size response has been extended from 10 to 20 micrometers, and several component and packaging changes have been incorporated to make the unit more suited to stack particulate survey applications.

The completed instrument was tested at a coal fired electric power generating facility. During the test a cascade impactor was used as a referee device and both instruments were run side by side in the outlet duct of the electrostatic precipitator.

The results show an excellent correlation between the two instruments with regard to the identification of a 1 μm diameter peak in the particle size distribution. A second peak around 20 μm was defined by the optical instrument but could not conclusively be confirmed through the impactor data. The optical instrument handled well during the field test and was delivered to EPA for additional testing.

This report is submitted by Leeds and Northrup Company in fulfillment of Contract No. 68-02-3253 for the U.S. Environmental Protection Agency(EPA). This report covers work performed over the period from September, 1979, to August, 1980.

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SECTION 1

INTRODUCTION

A prototype real-time in situ monitor was developed and constructed on EPA Contract 68-02-2447 to measure particle size distribution of respirable particles in the 0.2 to 10 μm range.[1] The purpose of this project was to add a channel to cover the 15 μm size range so as to include the upper cut-off of the inhalable particulate emmissions from stationary sources.

The addition of the large particle channel required a series of changes in the optical and electronic assemblies of the original instrument. In the process of incorporating these changes, the latest available components were selected and packaging improvements were made, resulting in an instrument optimally suited for survey work and stack particulate analyses. The new instrument measures the size distribution in the 0.2 to 20 μm range in five size fractions, using a low power helium neon laser light source.

The modified prototype instrument was tested at a coal fired electric generating plant. Referee measurements were made with a cascade impactor. Both instruments reported a strong peak in particle size around one μm in diameter. The optical instrument data suggested a bimodal distribution, with a second peak in the 15 μm channel. This could not be definitely confirmed with the impactor data, although one of the four runs did indicate a bimodal tendency.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this work was to modify and test a prototype optical stack particulate monitor by the addition of a channel responding to particles in the 15 μm size range. This was successfully accomplished. Tests in the laboratory showed results that agreed with expected size distributions of several sample materials which were in the 0.2 to 20 μm size range of the instrument. The field tests, conducted at a coal fired electric utility plant, provided size distribution data which were in excellent agreement with results reported by a referee inertial impactor.

A secondary goal of this project was to improve the reliability and portability of the instrument to make it more suitable for stack survey work. The modified prototype unit is lighter and smaller than the original, and the operational improvements, such as ease of alignment and reliability of operation were demonstrated during the field trial. Size distribution data is computed and displayed immediately upon the conclusion of the signal collection sequence. In all the field trial data, the optical and impactor data indicated a strongly peaked distribution around the 1 μm size. The optical instrument indicated another peak in the 15 to 20 μm range, but this could not be definitely confirmed by the impactor due to the limitation of its large particle size response.

Recommendations for future work include additional field trials at sites with different types of fuel, clean-up devices, and loading conditions. To be most useful for gaining confidence with this instrument, measurements with referee sizing instruments should be taken in parallel.

There may be significant value in developing an on-site technique to provide the operator with a quick means of checking the calibration of the unit. Although there are no moving parts in the prototype which would affect the calibration, some form of indicating calibration status is desirable. A continuous monitor of optical alignment is provided in the instrument. This feature was found to be very useful in maintaining alignment in the stack.

Another area for future consideration is modification of the electronics to optimize the gain for loadings at or below the original design criteria range of 0.01 to 0.1 grams/meter^3. This could be done by changing the feedback resistors at the detector board and trimming the electrical offsets to lower values.

In summary, this prototype should prove to be very useful for field survey work for analysis of size distributions from utility stacks.

SECTION 3

PRINCIPLES OF OPERATION

The stack particulate monitor measures the light scattered by particles passing through a 2.5 cm by 36 cm slot at the end of a 152 cm (5 foot) long probe. The light source is a 2 milliwatt helium neon laser, which emits a coherent beam at 0.6328 umeters. The scattered light signals are proportional to the volumes of particulate material present in each of five size fractions. Six scattered light readings are taken at precisely determined angles, and a digital microprocessor calculates a five channel, volume-by-size histogram, covering the size range from 0.2 μm to 20 μm.

The computational algorithms for particles larger than 3/4 μm in diameter, are based on simple diffraction theory. Rigorous Mie scattering theory is applied for the sub-micrometer particles. Spherical shaped particles are assumed for all the theoretical modelling.

The next two sections review the principles of light scattering employed. They are intended to provide a brief overview of the approach. Much more detail can be found in the references cited in those sections.

SIMPLE DIFFRACTION THEORY

For spherical particles that are much larger than the wavelength of light, the majority of scattering from an incident collimated beam is confined to relatively low forward angles (within a few degrees of the direction of a probe beam). A well defined concentric ring structure, the Airy pattern, is formed at the rear focal plant of a lens used to collect the scattered light.[2]

Approximately 84% of the scattered light is in the first, or central ring. The perimeter of this central ring, expressed as a scattering angle, θ, is a function of the wavelength of the source, λ, and the particle diameter, D, where

$$\theta = 1.22 \lambda / D \qquad (1)$$

As the particle diameter decreases, the Airy pattern increases in size.

The optimum position to detect scattered light from a particular size range is inside the first ring. Thus, for the new channel designed to respond to 15 μm diameter particles, the best observation angle for a wavelength of .6328 μm is well inside the 2.95° boundary angle specified in equation (1). Smaller sizes are sensed at progressively larger angles. However, scattered light from other particle sizes will, in general, be present at all forward angles.

In this instrument, four forward angles are measured, 1.3°, 2.6°, 5.1°, and 9.5°. Through a microprocessor algorithm, the influence of particles outside a particular size range of interest can be minimized or reduced to zero. This eliminates the severe constraint imposed by other scattering instruments which require only one particle to be present in the beam at a time. More details on this approach to particle analysis using forward scattering of light can be found in references 3 and 4.

RIGOROUS SCATTERING THEORY

Simple diffraction theory provides an excellent approximation to the low angle forward scattering pattern for the entire range of particle sizes of interest. However, as particles become smaller, the pattern over the first ten degrees becomes increasingly more uniform. Consequently, forward scattering is not adequate for sorting out size distributions when sub-micrometer particles are simultaneously present with larger sizes.

Rigorous scattering theory, or Mie theory, [5, 6, 7] is required to predict intensity distributions for higher angles. This theory indicates that at 90° to the probe beam under certain illumination conditions, the amount of scattering per unit volume of particulate material reaches a peak when the particle size is approximately half the wavelength of the light used as the probe beam. The measurement conditions require that two orthoganol polarizations of light be used. Then, the difference in the scattered light intensities for the two polarizations is proportional to the volume of material present in that size range.[8] Different size ranges can be selected by using different wavelengths.

This principle was used in the earlier work, as cited in the introduction, to build a prototype stack monitor, and extensive details of that principle and its implementation are found in that final report.[1]

The light source selected for this unit is a helium-neon laser with a wavelength of .6328 μm. Thus, the sub-micrometer channel has its peak response at approximately 0.3 μm, with a half width extending from 0.2 to 0.4 μm.

SECTION 4

DESIGN OF THE PROTOTYPE

Modification of the original instrument to extend the particle response to 15 μm involved a number of significant changes in the design. When appropriate, these changes were made so as to accommodate improvements suggested from field trial experience with the first unit. The pertinent aspects of the new design are discussed in the following paragraphs.

LIGHT SOURCE

The original unit used a xenon arc source for both forward and 90° scattering. For this use, an arc source must be accurately collimated to cause a minimum of beam divergence, and still provide sufficient light to make the scattering measurement. Furthermore, for the loadings of interest, the flux collection lens needs to be offset from the main beam to eliminate stray light from dust and dirt on the lens surface. These constraints make it impossible to collect light from particles in the probe slot region using the shallow angles necessary to respond to the 15 μm size range. The only approach deemed feasible was to replace the arc lamp with a low power (2 milliwatt) helium-neon laser. The narrow, well collimated beam permits light collection at low forward angles, while allowing the collection lens to remain offset from the probe beam. Substitution of the laser for the arc lamp also avoids transient problems arising from the high starting voltage generated by the arc lamp power supply. Furthermore, it permits the elmination of the separate arc lamp power supply weighing 25 kg (55 pounds).

PROBE SECTION

The probe is 152 cm long (5 feet), 9 cm diameter (3½ inch) stainless steel tubular structure, with a 2.5 by 36 cm slot at the tip to pass a particle laden gas stream. Its dimensions, the supporting structure, and the exterior sheath of the probe remain the same as the original prototype. Modifications were made to the optical collection system at the tip of the probe, as required to accommodate new scattering angles.

COLLECTION LENS SYSTEM

The new collection lens system has a 2.5 cm (1 inch) aperture. The aperture width is greater than the original lens due to the need to collect light over a broader range of angles. However, this larger aperture means the spherical aberration from a single element lens is very severe, so a two-lens system was specified, using commercially available lenses.

Without a custom lens design, however, field curvature remains uncontrolled. To compensate for this, the collection aperture plane is tilted by 15°, as shown in Figure 1. This reduces the blurring caused by the remaining aberrations to an acceptable level, and allows for good definition of the scattering angles encompased by each aperture.

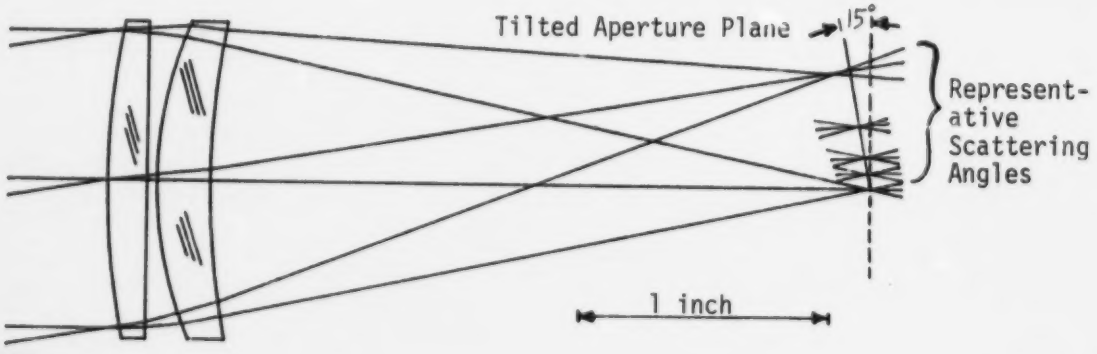


Figure 1. Design of collection lens system showing tilted aperture plane used to minimize the effects of aberrations.

The collection aperture plane consists of four openings, centered at 1.3°, 2.6°, 5.1°and 9.5°, relative to the laser beam axis. The changes in wavelength and lens focal length required by the new large particle channel required a modification in the size and shape of the collection apertures, so new fiber optic cables were designed and purchased for forward scattering. These cables, as in the original design, bring the optical signal from the high temperature environment of the stack to the transceiver, where silicon detectors measure the intensity of the scattered light. The two 90°collection apertures and fiber cables are the same as used in the original unit, as they did not need to be modified.

BEAM ALIGNMENT SENSOR

For the small scattering angles required for the 15 μm channel, pointing errors of a few tenths of a degree are a significant fraction of the desired scattering angle and can produce errors in the measurement. Therefore, another change required to successfully measure the large particle fraction is the addition of a beam alignment sensor.

Located at the tip of the probe, in line with the axis of the laser, is a fiber bundle just slightly larger then the laser beam diameter. This fiber cable carries light to the transceiver, where a separate silicon detector measures the signal intensity. The signal is displayed on a meter at the transceiver end, as shown in Figure 2, circle 3. This fiber, detector and meter arrangement provides adequate protection for sensing of alignment shifts. A beam steering device, located inside the transceiver and accessible through two small ports, circles 1 and 2, in Figure 2, permits easy adjustment of the beam either in or out of the stack.

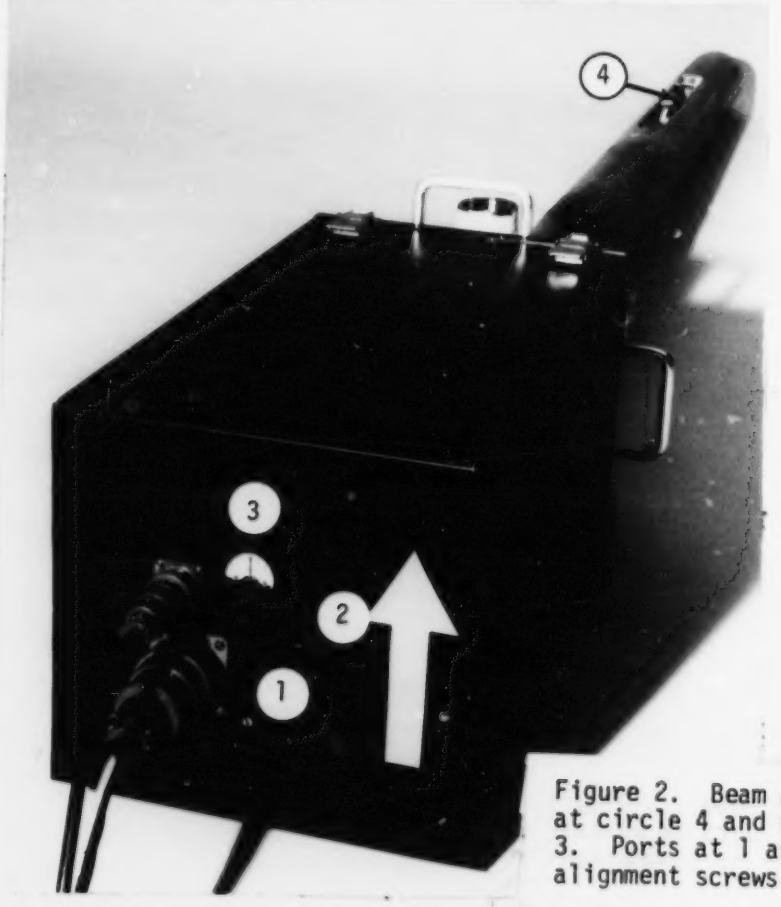


Figure 2. Beam alignment is detected at circle 4 and reported at the meter, 3. Ports at 1 and 2 provide access to alignment screws.

Formerly, after passing the sample slot region, the probe beam continued out through a hole in the end of the tip. The tip is now sealed, and includes a light baffle system so that the laser beam is not reflected back into the sample region.

TRANSCEIVER DESIGN

The transceiver is attached to the probe, but remains outside of the stack. The new transceiver assembly is 51 cm long by 25 cm square (20 inches long by 10 inches on a side), and is only 54% of the volume of the transceiver of the earlier prototype. This is due to the replacement of the arc lamp by the helium neon laser and the elimination of a rotating optical filter and polarizer wheel. A chopper wheel (15 Hz) provides a means of distinguishing the optical signal from ambient background light.

Six scattered light signals are measured continuously by the detectors located in the transceiver. Six low-noise silicon detectors are mounted on a circuit board assembly designed and built for the original unit. Additional silicon detectors are required for the beam alignment and laser beam strength signals, so a total of eight signals are acquired.

At the junction between the probe and the transceiver is the air manifold, which distributes the required purge air into the probe. This manifold was modified slightly to incorporate an air connection housing supplied to us by the EPA. The connection to the air blower is now made by a single 2-inch diameter flexible hose. The transceiver no longer needs air flow for cooling.

ELECTRONICS SYSTEM

Major microprocessor software changes were required to accommodate the addition of the large particle response and the associated changes due to the replacement of the light source. As a result, the original 8008 microprocessor package was not adequate and furthermore was not compatible with the new software development system recently acquired by Leeds & Northrup. This system has proven to shorten the program debugging time dramatically in similar situations. Thus, the 8008 microprocessor was replaced with a Z-80 unit which is more compact, has more storage and flexibility and is compatible with the L&N software development system.

The microprocessor rack, control panel, and a new, compact printer and paper take-up reel are all incorporated in one 9.1 kg (20 pound) portable, weather resistant aluminum box. The control panel, shown in Figure 3, contains the sample time, gain, and function controls. Results are indicated on a four segment LED display, and simultaneously recorded on the alphanumeric printer. Once the probe is inserted and aligned, all

operations are controlled at the console. This control panel can be sealed by closing the top, although the display remains visible through a plexiglass window in the cover.

A second, smaller aluminum box contains the electronics power supply. This is separated since heat built up in a sealed container would adversely affect other electronics housed in the same box.

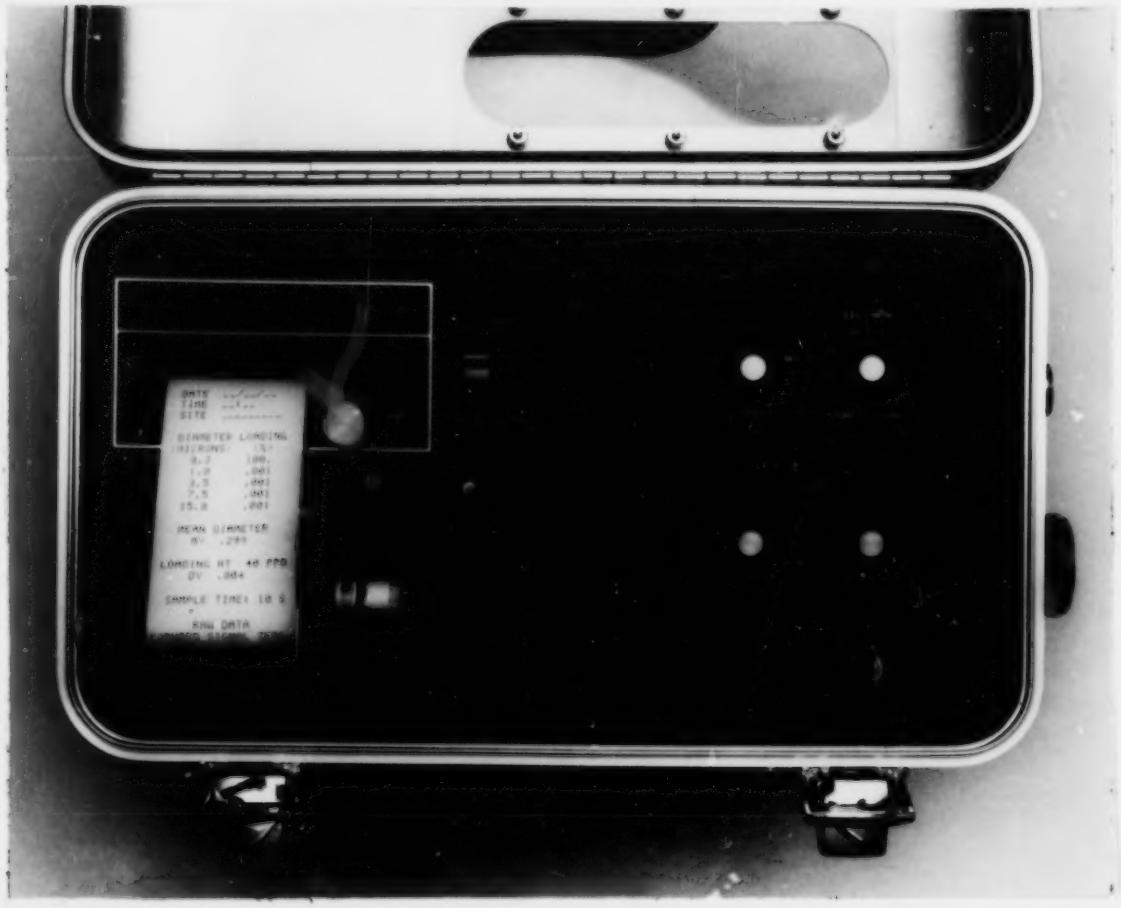


Figure 3. Control panel, incorporating operational function switches and 20 column alphanumeric printer.

MICROCOMPUTER SYSTEM

A block diagram of the microcomputer and associated electronic hardware is shown in Figure 4. The microcomputer is organized around the Pro-Log PLS-898 one card system. This system uses a Z80 microprocessor and has a memory capacity of 8K PROM and 2K RAM. Additional Pro-Log cards are used for input and output port expansion. A total of six input ports are provided for entering the digitized light signals and control panel switch settings. Eleven output ports are available for operating a four digit panel display and digital printer.

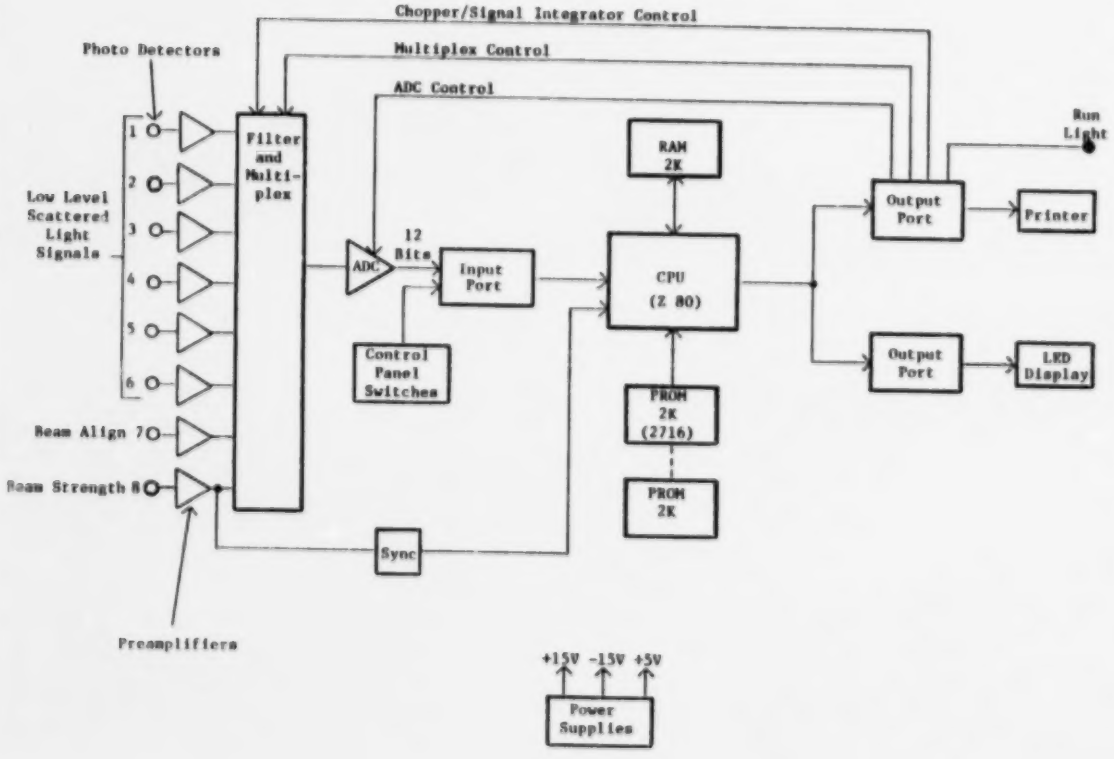


Figure 4: Electronics block diagram

ADC

The analog to digital converter is a 12 bit dual slope type with a maximum conversion period of six milliseconds. The converter is controlled by a pulse from an output port and is enabled at precise times to sequentially read the electrical signals from the eight detectors.

PLS-898 card

The PLS-898 one card microcomputer consists of a Z80 microprocessor, memory and input/output ports on a single 4 1/2" x 6 1/2" card. The memory elements are 2716 (2K x 8) PROM chips and 2114 (1K x 4) RAM chips. The PROM storage has a maximum of four 2716 chips for a total capacity of 8192 locations. The RAM is derived by using two 2114 chips to form a 1024 x 8 static read/write memory. Two additional chips can be added for a maximum capacity of 2048 RAM locations.

Input/Output ports

There are two 8 bit input ports and three 8 bit output ports on the PLS-898 card. The input/output capability has been expanded by using additional external cards. Each additional card consists of four 8 bit ports giving a total of 32 lines per card. One input card (Pro-Log 8114) is used along with the input ports on the PLS-898 card to enter the various input signals from the A to D converter and control panel switches.

Two output cards (Pro-Log 8115-1) are needed to operate the seven-segment LED display and the printer. An output line is also used to operate a front panel "Run" light which flashes during the data gathering cycle. Other output lines control the A to D converter, filter and multiple circuits.

Display

A four digit 0.4" LED display is used on the operator's panel to indicate the particle distribution, mean diameter and total volume loading. All decoding for the display is done in the microcomputer and the display is driven from four output ports.

Printer

A 20 column printer is used to produce a permanent record of the output data. The printer requires a parallel 8 bit ASCII format and is driven from a single output port. A full set of alpha-numeric characters is available, allowing labels and error messages to be printed along with the data.

Power Supply

The power supply assembly consists of a 5 volt (6a.) supply for the digital circuits and a ± 15 volt (100 ma.) supply for the analog circuits. The supplies are located remote from the microcomputer system in a separate enclosure so the heat generated does not disturb the microcomputer operation.

OPERATIONAL SUMMARY

Before the instrument is installed at a stationary source, optical background readings are measured, and then automatically stored in the microprocessor memory. These signals arise from scattering of the probe beam as it passes through lenses and windows in the optical system. They constitute fixed offsets and are subsequently subtracted from the actual scattering signals.

During a measurement cycle, the microprocessor controls the data acquisition for a period from 5 seconds to 12 minutes, as determined by the control panel time setting. At the end of this period the accumulated signals are averaged by the time of integration, and the background readings are subtracted. The microprocessor then calculates the particle size histogram from the six scattered light signals and uses the beam strength, detector 8, for normalization when computing the total loading. A mean particle size, called the "volume mean diameter,"[3] is then calculated from the histogram.

A typical display of printer output data is shown in Figure 5A. The date, hour and site blanks are filled in by the operator. The histogram distribution and volume mean diameter M_V, are printed below that. The control panel settings for system gain (40, 100, or 400 ppb) and sample time (in seconds) appear at the bottom, along with the volume loading, D_V, a signal proportional to the concentration of material in the probe during the measurement.

A longer format print-out can be selected giving the previously described data along with the signal and optical background or baseline values for each of the eight detectors. This is shown in Figure 5B.

The microprocessor checks other aspects of the data acquisition and will print error messages for misalignment, overrange of the signals, and failure to set zero. The error messages are shown in Figure 5C.

SUMMARY OF THE DESIGN

A photograph of the prototype stack particulate analyzer appears as Figure 6, showing the transceiver - probe assembly, A, the control console, B, and the electronics power supply box, C. The air purge blower, which connects to the transceiver at the manifold at circle 1, Figure 6, is shown in Figure 7.

Table 1 contains a summary description of the modified stack particulate monitor. The table includes the operational characteristics of the prototype, and size and weight specifications. A detailed description of operating procedure, maintenance, diagnostics, troubleshooting and service is contained in an instruction manual, prepared separately and supplied with the instrument.

"Print 1"
(Short form)

```
DATE  --/--/--
TIME  --:--
SITE  ---------.

DIAMETER LOADING
(MICRONS)   (%)
  0.3       14.5
  1.0       76.9
  3.5       8.52
  7.5       .001
 15.0       .001

 MEAN DIAMETER
   MV  1.11

LOADING AT  40 PPB
    DV  1848

 SAMPLE TIME: 10 S
```

A

"Print 2"
(Long form)

```
 DATE  --/--/--
 TIME  --:--
 SITE  ---------
 ----
 DIAMETER LOADING
(MICRONS)   (%)
   0.3       14.5
   1.0       76.9
   3.5       8.52
   7.5       .001
  15.0       .001

  MEAN DIAMETER
    MV  1.13

LOADING AT  40 PPB
    DV  1737

 SAMPLE TIME: 10 S

      RAW DATA
FORWARD SIGNAL ZERO
  1.3    270.  8.00
  2.6    692.  13.0
  5.1   1566  11.0
  8.5   1815  7.00

90 DEGREES


  RED 1  707.  7.00
  RED 2  636.  8.00


BEAM
  FOCUS  867.  1167
  POWER  1532  1925
```

B

Error Messages

```
BAD  ALIGNMENT
```

```
12.5 %
OVERRANGE FACTOR
```

```
ZERO NOT SET
 FOR THIS GAIN
ZERO NOT SET
 FOR THIS GAIN
```

C

Figure 5. Samples printouts from a typical run. Short form in A, long form, complete with raw data, in B, and the error message library in C.

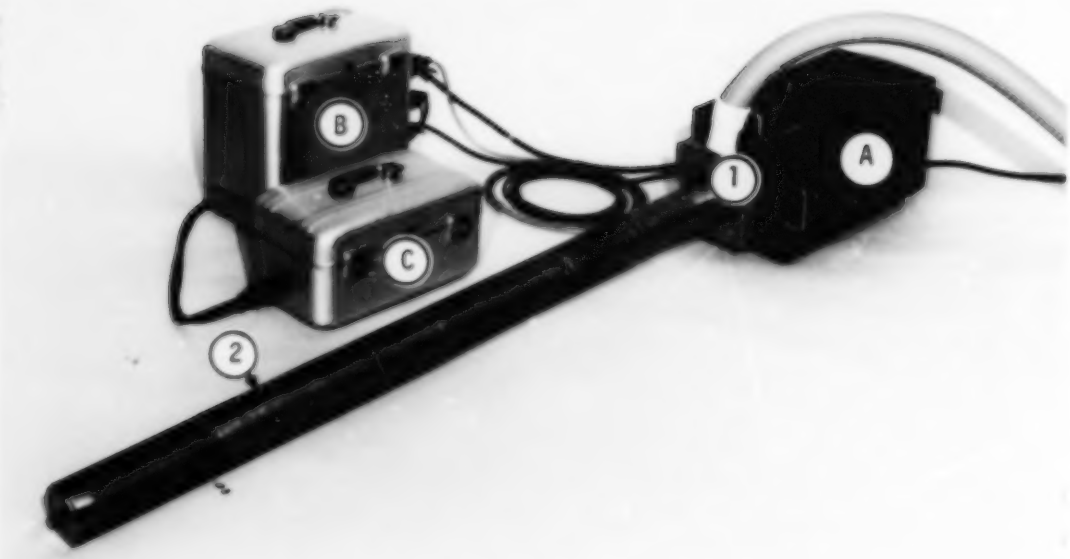


Figure 6. Prototype stack particulate monitor showing:
A) transceiver probe
B) electronics console box and
C) electronics power supply

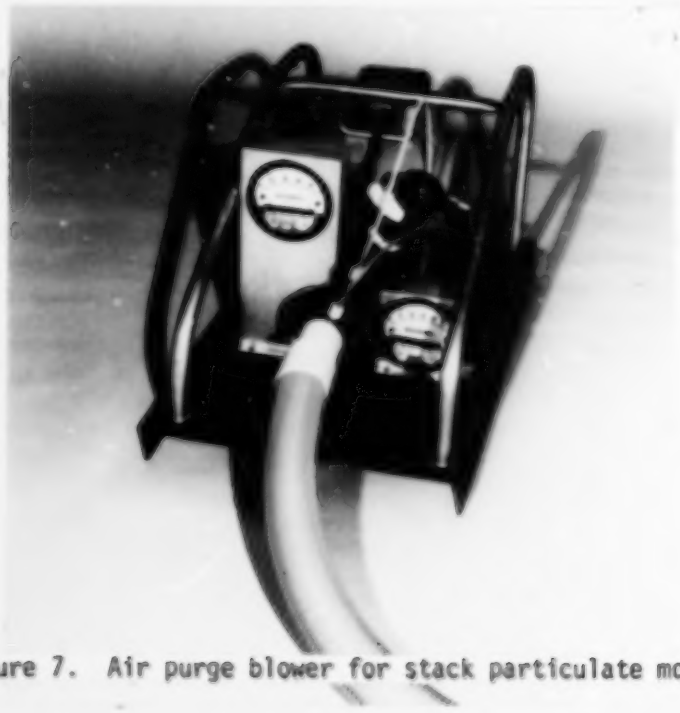


Figure 7. Air purge blower for stack particulate monitor.

TABLE 1. OPERATIONAL CHARACTERISTICS OF STACK PARTICULATE MONITOR

Size Range (Particle Diameter)	0.2 to 20.0 μm
Size Discrimination	Five volume fractions with centers at 0.3, 1.0, 3.5, 7.5, 15 μm
Mode of Operation	Low angle forward scattering and 90° polarization dependent scattering
Antipated Loading Range	0.01 to 0.1 grams of material/meter^3 (.023 to .23 grains/ft^3) or 4 to 40 parts/billion by volume (with s.g. of 2.5)
Operational Range	4 to 400 parts/billion (.023 to 2.3 grains/ft^3)
Measurement Time	Signal integration time selectable from 5 seconds to 12 minutes (including a 6-minute position)
Duct Velocity	1.5 to 18 meters/second (5-60 feet/second)
Duct Temperature	260° C maximum (500° F)
Instrument Temperature	2° C to 43° C (35 to 110° F)
Power Requirements	One 20A, 115 volt, 60 Hz outlet
Physical Specifications	
Probe Dimensions	152 cm long (60 inches) by 9 cm diameter (3½ inches)
Sample Slot Dimensions	2.5 x 36 cm (1 x 14 inches)
Transceiver-Probe Assembly	203 x 25 x 25 cm, 31.8 kg (80 x 10 x 10 inches, 70 pounds)
Control Console	38 x 41 x 25 cm, 9.1 kg (15 x 16 x 10 inches, 20 pounds)
Electronics Power Supply	23 x 41 x 25 cm, 6.4 kg (9 x 16 x 10 inches, 14 pounds)
Blower	74 x 48 x 43 cm, 22.7 kg (29 x 19 x 17 inches, 50 pounds)
Probe Material	Type 316 Stainless Steel (except for optical components)

SECTION 5

CALIBRATING THE PROTOTYPE

The stack particulate analyzer measures five size fractions, with channel centers at 0.3, 1.0, 3.5, 7.5, and 15 μm. Individual channel response functions are shown as the family of curves in Figure 8. The curve on the far left is derived from the 90° scattering signals, and the response is calculated from Mie scattering theory. The other four curves are computed from simple diffraction theory, and are measured using low angle forward scattered light signals. The wide response of the one μm channel, the second curve from the left, occurs because the forward scattering pattern of the one μm size particles does not change rapidly over the first 10 °. Thus it is harder to isolate that size fraction using forward scattering.

These channel responses are produced by combining the signals received at the individual detectors in a predetermined algorithm. The calibration procedure involves adjusting the gain and correction constant for each of the six scattered light detectors so that the proper balance of signals is received by the microprocessor.

The desired signal at a given angle, $S(\theta)$, is the product of several factors, as outlined in the following equation:

$$
\begin{aligned}
S(\theta) = {} & \text{Scattering per particle at } \theta \times (\text{Particle Distribution}) && \text{(a)} \\
& \times \text{Loading} && \text{(b)} \\
& \times \text{Detector Gain} && \text{(c)} \quad (2) \\
& \times \text{Collection Geometry} && \text{(d)} \\
& \times \text{Fiber Transmission} && \text{(e)} \\
& \times \text{Correction Constant (added in processing)} && \text{(f)}
\end{aligned}
$$

Each term has an influence in the calibration procedure, as follows:

(a) The light scattered at a particular angle is an integral of the product of the scattering per particle and the particle size distribution. Calibration is simplified when the particle size distribution is monodisperse or the scattering function is independent of size. Since it is not feasible to generate a monodisperse aerosol of sufficient concentration to permit its use for calibration, moderately broad aerosols were used.

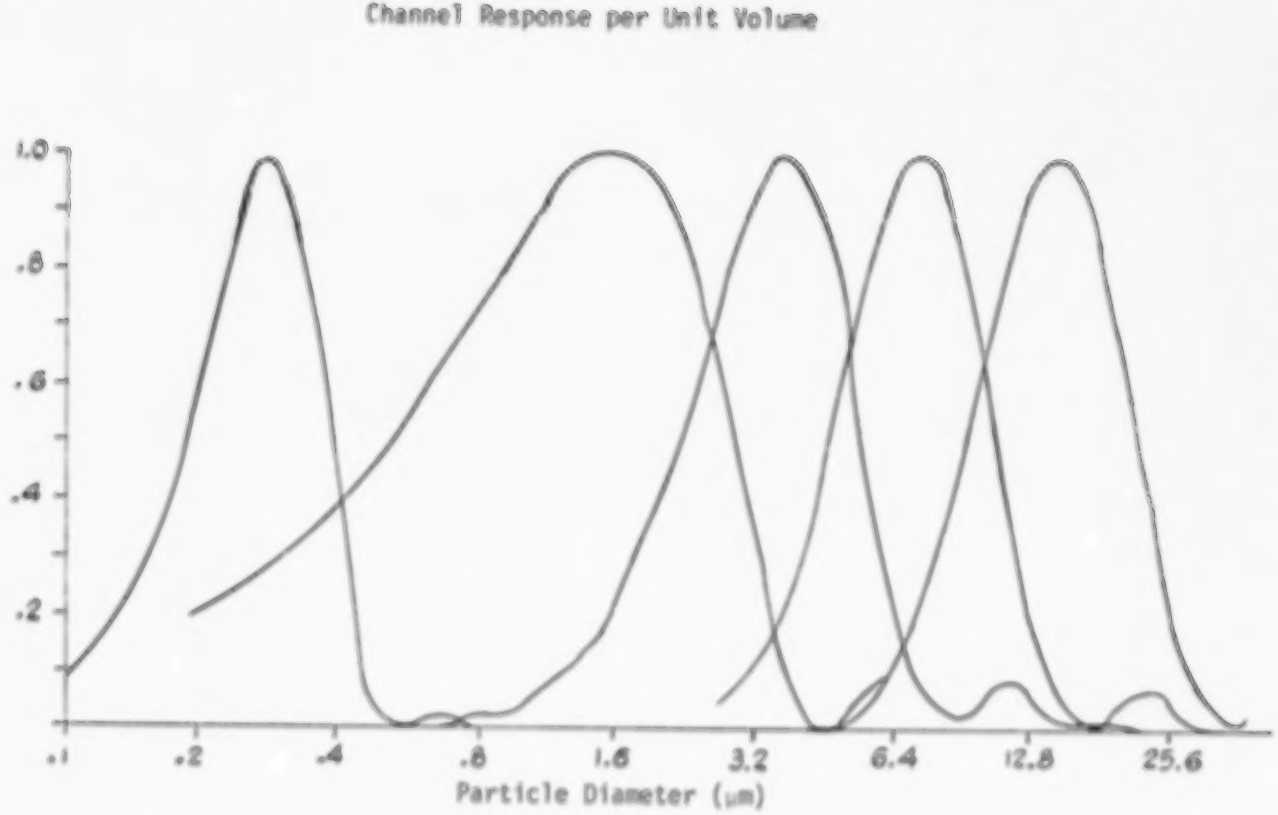


Figure 8. Response curves for the five channels, showing the response per unit volume as a function of size. The curve on the left is derived from 90° measurements, and the other four are from forward scattering.

However, in the special case of an aerosol suspension of submicron particles, the low angle forward scattering distribution does not change with size. Thus, the ratio of scattered light signals at any two angles is independent of the sizes within the suspension. This principle is the key to final successful calibration of the forward scattering portion of the system.

(b) The loading or concentration of the material has a linear effect on the signal strength. The anticipated loading range determines the appropriate gains for the individual detectors.

(c) For a given loading, the product of loading and the gain of each detector preamplifier should produce signals within one range of the digital electronic circuitry. Initially, the detector preamplifiers are set to approximate values. During tests with actual distributions, the exact balancing is determined and applied through the correction constant, (f).

(d) The collector lens is located slightly off axis, as mentioned in Section 4. As a result, the forward angle detectors view overlapping but not identical regions of the sample slot. The collection geometry does not change once the probe is assembled, as there are no moving parts in the probe. Once determined, these values remain fixed. The two 90° scattering detectors view the sample region through symmetrically positioned ports at the sides of the probe, so their collection geometries are the same.

(e) The fiber optic cables are fixed permanently in the assemblies which collect the scattered light. Fiber transmission losses may occur due to breakage of individual optical fibers by flexing during manufacture or assembly, but once installed the cables are held firmly in place. The transmission efficiency and collection geometry product is measured and corrected as a single factor.

(f) The correction constant is computed for each scattering angle and stored in the microprocessor algorithm. It brings all signals to a uniform scale so that the signal variations are due only to particle size distribution effects.

There is no unique or ideal referee material for calibration, and calibration process involves several steps. Different materials were used to set up the correct balance of signals and later to verify the performance of the prototype unit. The major steps are outlined here.

(1) During assembly, the light collecting apertures were checked for alignment and adjusted to insure that the correct angles were being measured.

(2) Di-octyl phthalate (DOP), a transparent liquid with an index of 1.49, was dispersed as a droplet suspension by a Phoenix Precision Aerosol Generator. This creates a well-controlled distribution in the 0.2 to 3 μm size range. The loading is controlled by the pressure and flow rate of the dillution air.

The actual signals were extrapolated to those expected for a uniform distribution of particles at 40 parts per billion, and the gains were set accordingly. Individual detector preamplifier gains were adjusted so that this hypothetical, uniform distribution would provide signals in the mid-range of the analog to digital converter. Once set, the gain of each channel relative to the others was accurately measured by illuminating a fiber bundle with a stable source and measuring the light level at the other end with each of the six detectors.

(3) The collection geometry and fiber transmission product at each angle is measured accurately only by knowing the scattered light distribution as a function of the angle. One candidate material for this step is fresh, filtered cigarette smoke since the majority of the particulate volume is well below one μm in diameter.[9] For this case, the forward scattering pattern does not change with particle size.

The aerosol test chamber was filled with tobacco smoke, generated by drawing air through filtered cigarettes. A correction constant is thus defined for each scattering angle, based on the difference between scattered light strengths observed and those predicted by Mie theory. The correction constant compensates for residual preamplifier gain errors, as well as collection geometry variations and fiber bundle transmission losses. The constants are programmed into the microprocessor as part of the data reduction algorithm.

(4) As a check for consistency, the instrument was then used to measure the aerosol distributions employed to calibrate it. Figure 9 shows the filtered cigarette smoke distribution, indicating a large percentage of the material in the 0.3 μm size channel, while Figure 10 shows the measured and manufacturer's specifications for the DOP aerosol suspension. In both cases, agreement between expectation and observation is quite good. Numerical data is provided in Table 2.

(5) To further check the performance and calibration, two other materials were run, burning red phosphorous, and solid glass spheres. The red phosphorous is used for tactical smoke screens, but no referee data was available. The instrument readings indicated roughly equal amounts of material in the 0.3 and 1.0 μm size channels. This is consistent with its intended tactical use, as particles in this size range are the most efficient scatterers per unit volume, and thus provide good obstruction. This data is shown in Figure 11.

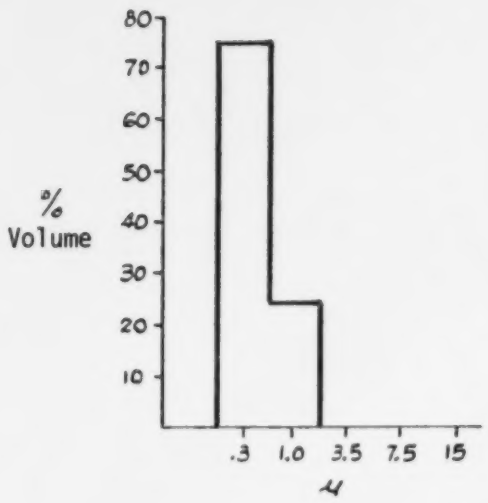


Figure 9. Calibration Run Using Cigarette Smoke

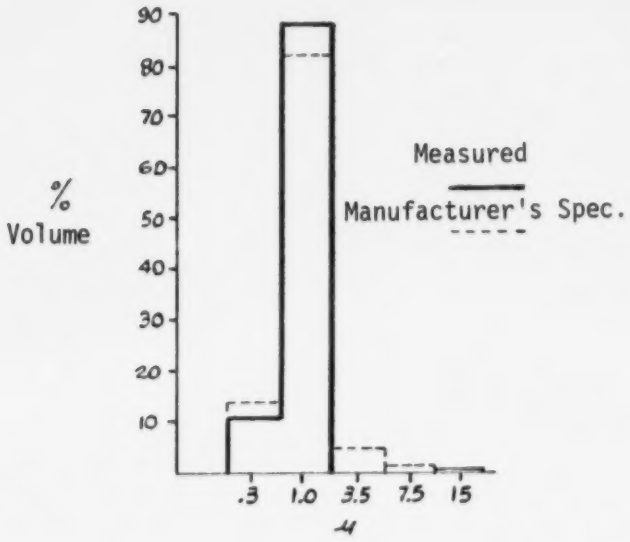


Figure 10. Calibration Using Phthalate Aerosol from Phoenix Generator

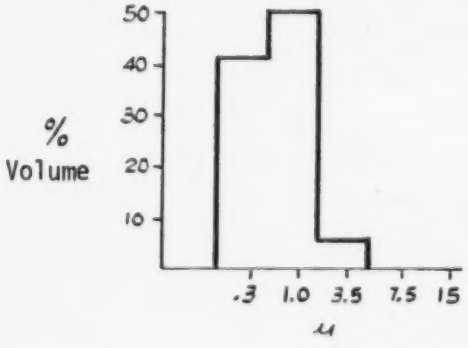


Figure 11. Calibration Run Using Burning Red Phosphorous

TABLE 2. SIZE DISTRIBUTIONS AS REPORTED BY THE INSTRUMENT IN LABORATORY TESTS

Particle Size Channel (μm)	Cigarette 6/13/80	Red Phosphorous 6/13/80	Phoenix 6/10/80	Phoenix Manufacturer Spec.
0.3	75.5	42.6	11.4	13
1.0	24.3	50.8	88.1	82
3.5	.0	6.4	.0	4.3
7.5	.0	.0	.0	1.0
15.0	.1	.0	.4	0.0

The solid glass spheres, from Potters Industries, Inc., are specified as "3 to 10 micron" size, but no additional data was provided or available. The beads were blown into a suspension chamber and exhausted through a duct containing the probe. The distribution measured is shown in Figure 11. No material is reported in the 0.3 μm channel, as expected, and most of the material is in the 3.5 or 7.5 μm region. The amount reported in the 1.0 μm channel may be due to the tail of the 1 μm response curve extending to the 3 μm area (See Figure 8.)

The material reported in the 15 μm channel is likely caused by clumping of the beads due to electrostatic charges introduced in the suspension process. To confirm this, microscopic examination of a bead sample collected during the test showed occasional clumping which would be reported as larger particles by the optical scattering instrument.

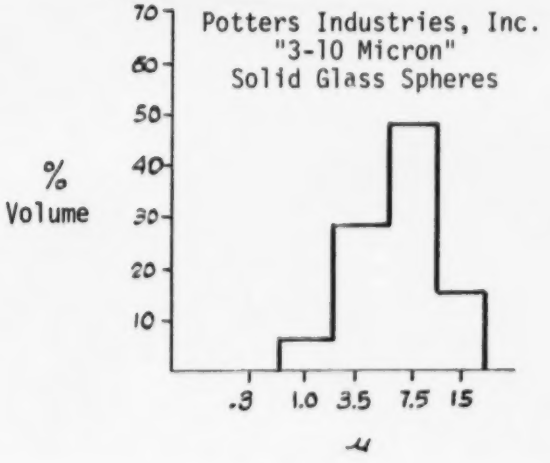


Figure 12. Distribution reported by Stack Particulate Monitor for an aerosol suspension of glass beads.

SECTION 6

FIELD TEST PERFORMANCE

During the week of July 21, 1980, the prototype instrument was tested at an east coast coal fired electric power generating station. L&N personnel used the prototype instrument to measure particle size distribution in a duct leading to the smoke stack. Personnel from Northrop Services, Inc., Environmental Science (NSI-ES), participated in the tests, taking data with a cascade impactor, and provided the necessary data analysis for that method. Six separate data sets were collected over two days. Four sets of data are presented here, two from each day.

All testing was performed at the outlet of the electrostatic precipitators and prior to the final exhaust fan as shown in Figure 13. The testing section was a vertical flow duct, approximately 32 1/2 ft. wide by 7 ft. deep. Sampling ports are located horizontally across the wide side of the duct (Figure 14). Each port is a 6-inch diameter flanged pipe, approximately 14 in. long. Two adjoining ports were selected to provide adjacent test points. A summary of the stack conditions appears in Table 3.

TABLE 3. STACK CONDITIONS DURING FIELD TEST

Stack gas velocity:	45 to 50 feet/second
Stack gas temperature:	230 to 300^{o} F
Gas pressure:	-2 inches of Hg
Direction of flow:	Vertical downward

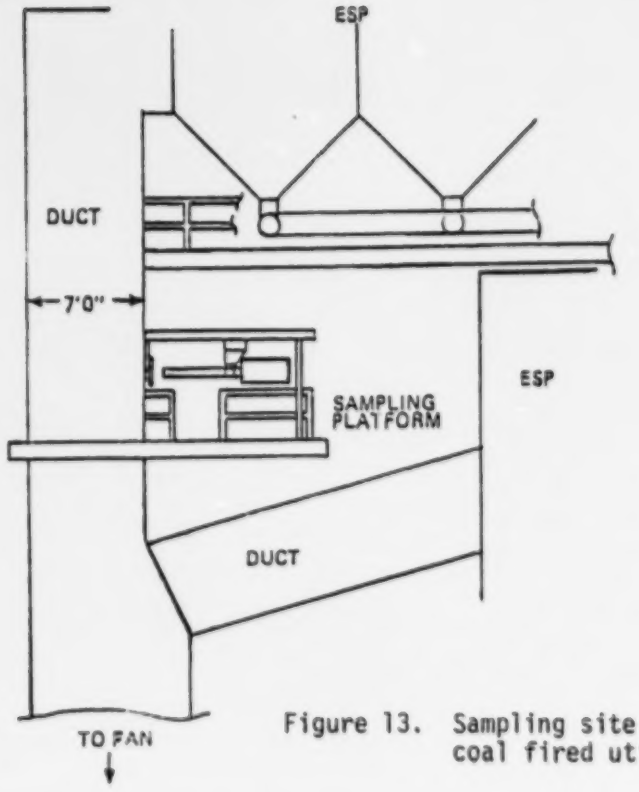


Figure 13. Sampling site at coal fired utility.

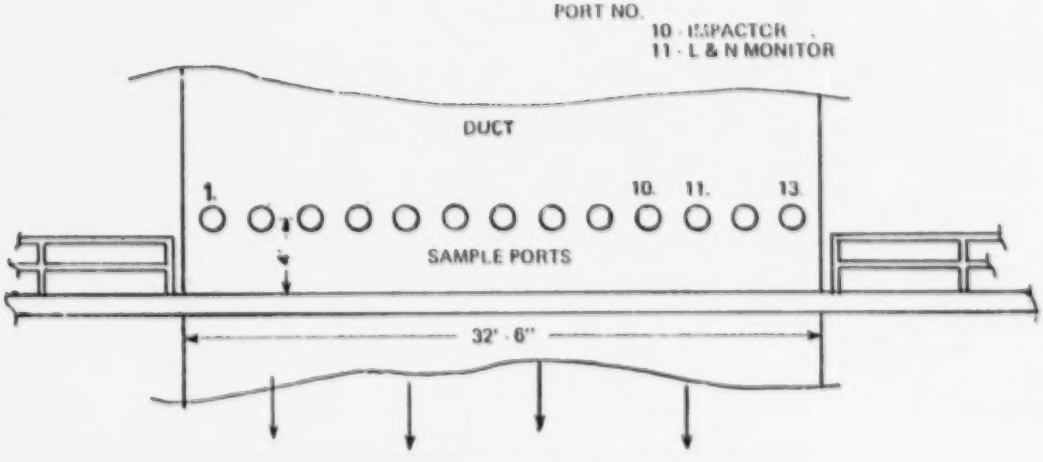


Figure 14. Sampling ports and test positions.

TEST PROCEDURES

All aerodynamic particulate sizing was performed using a University of Washington Mark III Cascade Impactor and necessary support equipment (Figure 15). The Mark III impactor is an in-stack, seven-stage unit incorporating a glass fiber backup filter. The impactor collection plates were prepared for testing by coating each plate with Apiezon H vacuum grease (Dow-Corning). The plates were heated at approximately 150° C; the plates as well as the glass fiber filters were then weighed.

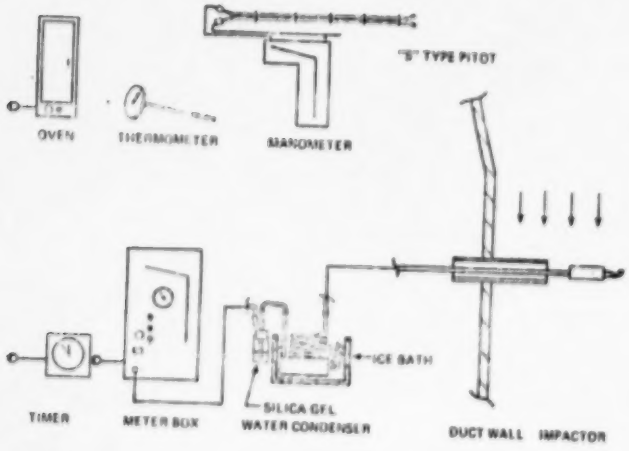


Figure 15. Sampling train and support equipment.

Prior to actual source testing, all in-stack and atmospheric measurements necessary for isokinetic and other calculations were recorded. Velocity head and stack differential pressure measurements were performed using a type "S" pitot. In-stack temperatures were measured using a thermocouple system attached to the end of the pitot tube. Velocity profile measurements were made up to 4.5 ft. into the duct at each of the three test ports, with the impactor sampling conducted at the point of both average velocity and close proximity to the optical instrument. The point used for sampling was approximately the mid-point of the duct or 4 ft. from the lip of the port flange. Nozzle size and sample flow rates were estimated using a nomagraph; ideally, a flow rate of 0.75 ft^3/min. is desired.

The impactors were preheated to stack temperature before sampling to avoid moisture condensation within the impactor body. The duration of each test was varied according to the stack opacity, knowledge that this coal unit was within particulate emissions standards, and the visual inspection of the previous impactor test. Sample runs varied from 20 to 40 minutes in length.

Several hours were required to make the preliminary measurements before the impactors were inserted.

The prototype optical particle size monitor was prepared within approximately one hour. All electrical cables were connected and the instrument was turned on to warm up the electronics. The optical alignment of the unit was adjusted using the external meter. The stack velocity, measured for the impactor runs, was used to set the purge flow rate on the blower. To facilitate insertion and removal from the stack during the tests, a suspension rail designed and built previously for this unit by NSI-ES was erected. A typical sample run took 6 minutes.

The test sequence is described in Table 4. Tests 1 and 2 were done on the first sampling day during which the boiler unit was operating at maximum output. On the second day, for tests 3 and 4, the boiler was operating at reduced output, and the particulate emissions were distinctly lower.

The prototype unit performed well during the tests. A six minute sampling time was selected, so several sets of size distribution data were printed during each impactor collection cycle. The following observations were noted during the field test:

1) Probe warp - As the probe temperature changed, the probe warped slightly and changed alignment. This did not cause any problem, since realignment was readily accomplished in the stack using the beam alignment sensor discussed in Section 4.

2) Sensitivity to ambient light - The 90^{o} detectors responded to ambient light more than expected during the set-zero procedure, so the probe slot was covered with duct tape for that step.

3) Inadequate gain for low loadings - The lowest loadings observed, reported to be less than 0.01 grams/NM^3, produced signals that were only a few counts of the 2000 count range. This indicates that the gain of the electronic system should be increased to provide better accuracy for the lowest loadings. This gain increase can be achieved by changing the feedback resisters in the detector amplifiers, or increasing the gain at the ADC.

4) Electrical offset adjustment - A small voltage bias on the detector circuit produces a slight electrical offset, which can lead to slight errors in the present data reduction algorithm for very low loadings. This can be corrected by fine tuning and trimming the offset potentiometers on the detector board. Without correcting the offset, the raw data available in the printout can be used with a different background correction algorithm to provide the most accurate results. This procedure was followed for presenting the data from the field tests.

TABLE 4. FIELD TRIAL IMPACTOR SCHEDULE

RUN #	DATE	START TIME	DURATION (Minutes)	CONCENTRATION (g/NM^3)
1	Tuesday, 7-22-80	2:58 p.m.	20	.021
2	Tuesday, 7-22-80	3:56 p.m.	30	.023
3	Wednesday, 7-23-80	9:59 a.m.	40	.008
4	Wednesday, 7-23-80	10:59 a.m.	40	.007

TEST RESULTS

Results for both optical and inertial instruments are shown in Figures 16 through 19, plotted as histograms of volume fraction per unit log interval of particle size. The optical data in each figure is indicated by the cross hatched histogram, while the impactor data is the heavier outlined histogram. Variations in the individual channel widths are due to the different principles involved in measuring the particle distribution.

The impactor data, provided by NSI-ES, were derived by plate weighings and computer assisted data reduction. A material density of 2.5 was assumed, and the channel edges were based on the aerodynamic separation properties of the individual stages of the impactor.

During each impactor run, continuous optical data measurements were made. The histograms shown are compiled from the time weighted average of the sequential optical data, which involved from 5 to 8 optical runs, depending on the length of the impactor run. The boundaries of the optical histogram are determined by the instrumental response as illustrated in the response functions in Figure 8.

The optical and inertial measurements agreed in some significant respects. In all runs both instruments reported a substantial size fraction to be around one μm in diameter with, in most cases, substantial reductions in the amount of material above the below the one μm size. The optical instrument consistently indicated a good deal of material in its largest size channel, which made the distribution appear bimodal. This could not be definitely confirmed by the impactor data available, although impactor runs 2 and 3 show a leveling off of the distribution, and run 4 does indicate a secondary peak in its largest particle channel.

Differences in the boundaries of the optical and inertial channels could account for the apparent inconsistency, especially if there were a significant fraction of material between 15 and 25 microns.

The optical signals in some cases were relatively low. Runs 3 and 4, especially, which were taken the second day when the particulate loading was at or below the design range of the instrument, may be subject to some error due to digitization round-off in the microprocessor. While the effect has been minimized due to the combination and averaging of several sets of data, confidence is higher in the accuracy of runs 1 and 2 than for runs 3 and 4. Relevant tabular data for the curves shown in these figures are presented in Appendices A and B.

The general agreement between the two methods is good. The size response question could well be resolved through further testing at other sites. There were some relatively minor technical problems, addressed elsewhere in the report, but none that should prevent the optical instrument from being used in other field tests. At the conclusion of this test, the prototype stack particulate monitor and its associated equipment were turned over to the EPA.

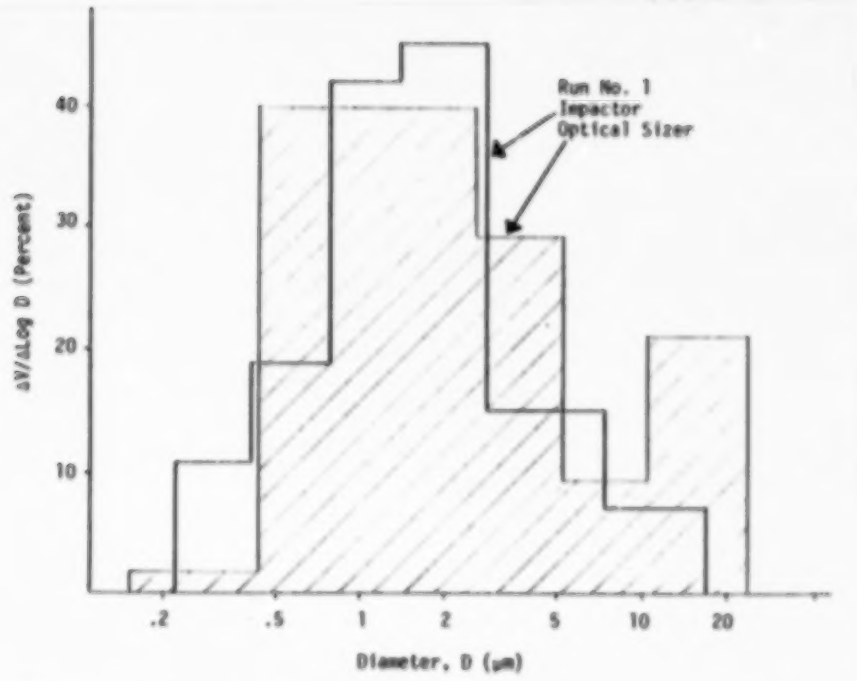


Figure 16. Particle size vs. volumetric concentration distribution for Test 1.

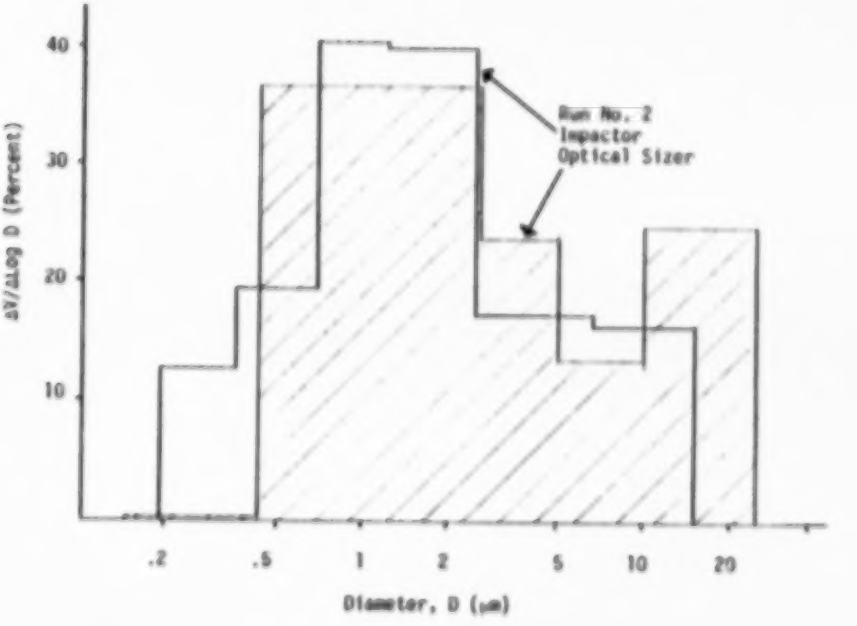


Figure 17. Particle size vs. volumetric concentration distribution for Test 2.

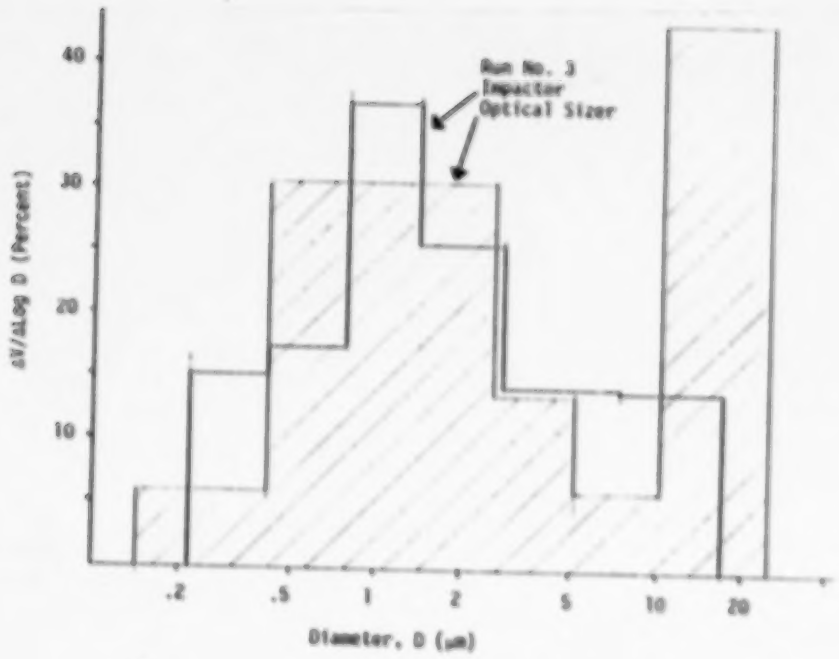
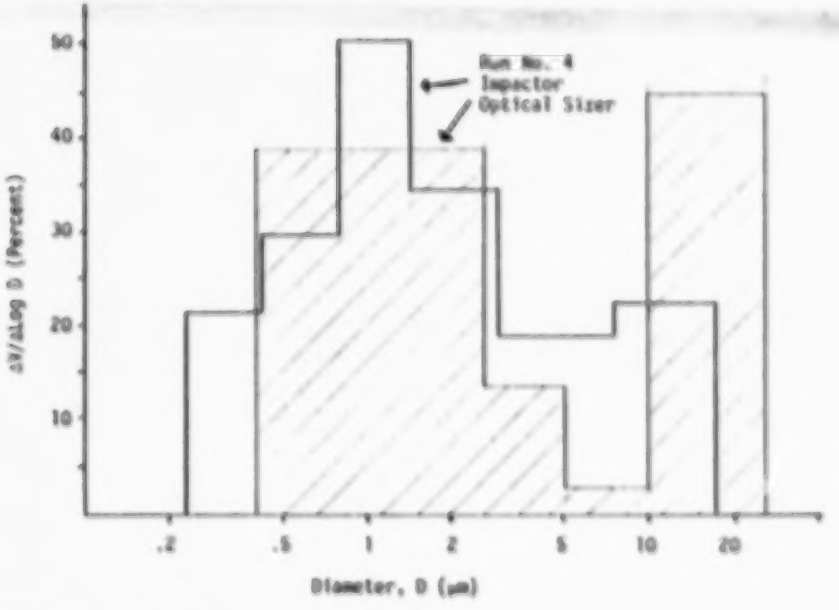


Figure 18. Particle size vs. volumetric concentration distribution for Test 3.



Fibure 19. Particle size vs. volumetric concentration distribution for Test 4.

SECTION 7

SUMMARY

A prototype optical stack particulate monitor was modified by the addition of a large size channel responding to particles in the 15 um range. The instrument utilizes low angle forward scattering and 90° polarization dependent scattering to measure 5 size fractions within the 0.2 to 20 um size range. Channel response peaks occur at 0.3, 1.0, 3.5, 7.5 and 15 um.

Several of the modifications made for the addition of the large particle response also provide a more compact and rugged unit which will be more suited for field survey use than the original instrument. A photograph of the new unit is shown in Figure 20.

A field test took place at a coal-fired utility plant, and referee measurements were made by a cascade impactor. The optical instrument and the impactor both identified a strong peak in the distribution in the 1 um diameter range. A second peak in the 15 to 20 um range was indicated by the optical instrument. One of the four impactor runs suggested that a secondary peak was present, but the largest size channel of the optical instrument extended above the range covered by the largest channel reported for the impactor, and the secondary peak could not be definitely confirmed.

This instrument should provide an alternative to cascade impactors, which may be especially attractive when rapid, on-line particle size analysis is needed.

Figure 20. Photograph of prototype stack particulate monitor, showing transceiver with five-foot probe and separate electronics control console. Not shown is the small electroncs power supply box and the blower used to provide purge air to the transceiver.

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* NTIS No. PB 292-751

APPENDIX A

Summary of Data from Optical Measurements
(Expressed as percent volume per unit log interval of particle size)

Impactor Run		1	2	3	4
Volume Histogram:					
Channel Designation	Response Range				
0.3 μm	0.15 to .4μm	1.5%	.2%	5.9%	0%
1.0 μm	.4 to 2.5μm	39.5%	36.7%	30.7%	38.9%
3.5 μm	2.5 to 5μm	29.1%	24.0%	13.6%	13.5%
7.5 μm	5 to 10μm	9.0%	14.0%	6.5%	2.8%
15 μm	10 to 25μm	20.9%	25.1%	43.3%	44.8%
Relative Loading (uncalibrated units)		51.4	43.6	16.3	12.5
# of optical runs taken		8	5	5	7

This data represents the average of all optical data runs taken during each impactor run.

APPENDIX B

Data From Impactor Measurements

Run	Stage	Sample Weight (µg)	Percent of Total	Cumulative Percentage	D_{50}	µg/Nm^3	
1	1	549	7.17	92.83	15.7	1508	VEL. = 47.5 ft/sec
	2	281	3.67	89.16	6.6	772	ACFM = 0.974
	3	694	9.07	80.09	2.53	1907	DNCF = 12.845
	4	1554	20.31	59.78	1.25	4269	NM3 = 0.364
	5	1186	15.50	44.28	0.70	3258	%150 = 100.4
	6	584	7.63	36.65	0.37	1604	
	7	320	4.18	32.47	0.20	879	
	F	2484	32.47			6824	
TOTAL		7652	100.00			21022	
2	1	1132	8.49	91.21	14.9	1976	VEL. = 49.6 ft/sec
	2	817	6.13	85.08	6.5	1426	ACFM = 1.014
	3	998	7.49	77.59	2.5	1742	DNF = 20.228
	4	1753	13.15	64.44	1.2	3059	NM3 = 0.573
	5	1376	10.32	54.12	0.68	2401	%150 = 100.0
	6	782	5.87	48.25	0.35	1365	
	7	474	3.56	44.99	0.19	828	
	F	5999	44.99			10469	
TOTAL		13331	100.00			23265	

Run	Stage	Sample Weight (µg)	Percent of Total	Cumulative Percentage	D_{50}	µg/Nm^3	
3	1	370	8.15	91.85	17.0	622	VEL. = 36.3 ft/sec
	2	322	7.09	84.76	7.4	541	ACFM = 0.772
	3	381	8.39	76.37	2.8	640	DNCF = 21.023
	4	488	10.74	65.63	1.4	820	NM3 = 0.595
	5	593	13.06	52.57	.78	997	%150 = 104.0
	6	307	6.76	45.81	.41	516	
	7	262	5.77	40.04	.22	440	
	F	1819	40.04			3057	
TOTAL		4542	100.00			7634	
4	1	412	10.84	89.16	17.2	713	VEL. = 35.8 ft/sec
	2	298	7.84	81.32	7.5	516	ACFM = 0.750
	3	285	7.50	73.82	2.9	493	DNCF = 20.421
	4	401	10.55	63.27	1.4	694	NM3 = 0.578
	5	463	12.18	51.09	0.79	801	%150 = 102.4
	6	300	7.89	43.20	0.42	519	
	7	207	5.44	37.76	0.23	358	
	F	1436	37.76			2484	
TOTAL		3802	100.00			6578	